Advanced Composites Development for Aerospace Applications

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Abstract

The evolution of composites applications in aeronautics from 1970 to the present is discussed. The barriers and challenges to economic application and to certification are presented and recommendations for accelerated development are outlined. The potential benefits of emerging technologies to aeronautics and their foundation in composite materials are described and the resulting benefits in vehicle take off gross weight are quantified. Finally, a 21st century vision for aeronautics in which human mobility is increased by an order of magnitude is articulated.

Keywords: Advanced composites, Aeronautics, 21st century vision

Introduction

Advanced composites have emerged as the structural materials of choice for many aerospace applications because of their superior specific strength and stiffness properties. First developed for military aircraft applications, composites now play a significant role in a broad range of current generation military aerospace systems. Commercial transport aviation has also witnessed a significant increase in adoption of composites during the past ten years. And there are currently a large number of general aviation aircraft with significant use of composite materials and structures that anticipate FAA flight certification in the near future.

Yet, there continue to be barriers and challenges to the expanded exploitation of composites technology for primary transport aircraft structures, i.e. wing and fuselage. These include damage tolerance, fuel containment, lightening protection, repair and nondestructive inspection, modeling and failure prediction and cost effective manufacturing. The successful resolution of these issues requires additional research directed at the underlying science through comprehensive programs of research and development. Development of standard engineering practices for exploitation of contemporary composites technology for near term applications can also be expected to benefit new aerospace products under current development.

The future composites technology will provide the platform for the next revolution in aerospace vehicle technology. With recent advances in science and engineering there are new emerging technologies that will likely accelerate the development of aerospace vehicle design during the next decade including: sensors and devices, intelligent materials and structures, active flow control, reliability-based design and certification, robust manufacturing technology, nanotechnology and biomimetics. Moreover, it is the strategic integration of these technologies that will provide for the next major gains in vehicle performance. Yet the integration of these technologies cannot be achieved with contemporary materials and structures technologies. Therefore, it is essential that significant effort be directed to develop the next generation composites technology.

Current Status

The applications of composite materials in aerospace products are pervasive today, having found their first applications in military aircraft in the early 1970's. The evolution of this important technology has been multifaceted with the initial phase led by the defense industry, significant advances in the commercial aircraft and rotorcraft industries and its most aggressive exploitation in the general aviation industry. Advanced composites can trace its origin to the invention of the boron filament in the United States and the carbon fiber in Japan/United Kingdom in the 1960's. The first production aerospace application was the horizontal stabilizer of the U.S. Navy F-14 in 1970, followed shortly thereafter by applications in the U.S. Air Force F-15 and F-16. During the decade of the 1980's commercial applications were initiated through the NASA ACEE Program. The Boeing 737 horizontal stabilizer was certified in 1982 and applications with composites approaching 10 wt.% were achieved with the Airbus 300 and 310, Boeing 737, 757 and 767, McDonnell-Douglas MD-82, 83 and 87 during the 1980's. The Airbus 320 was first commercial aircraft to exceed the 10% utilization. By 2000, applications approaching 30% weight savings had been achieved by the U.S. Air Force B2 and F-22 and the U.S. Navy V-22. The industry is now poised to develop commercial and military airframes with extensive composite wing, empennage and fuselage applications. The Boeing "Sonic Cruiser" and the 650-seat A380 Airbus will likely be the next examples of the use of composites in future commercial aircraft. Two new business jets with composite sandwich designs in pressurized fuselage have been recently undergone consideration for certification by the FAA. The Raytheon Premier I has been flight certified and the AASI Jetcruzer 500 is well into the process. Propeller-driven aircraft have also incorporated composite materials in their airframes. The PAC USA Lancair LC40-550FG and the Cirrus Design Corp. SR 20 were type certified in 1998 [1]. New rotorcraft vehicles include composites applications in airframe, rotor blades and rotor drive systems (main and tail). The Sikorsky S92 rotorcraft and the Bell Textron BA609 Tiltrotor are two such examples.

Barriers and Challenges: Economics and Certification

Barriers to expanded application to composite materials in aircraft are shared by the defense, commercial and general aviation industries. Manufacturing and non-recurring development costs continue to limit the rate of growth of the field. Current engineering practice is a test-based, building-block approach that is test intensive. Empirical design and process standardization and maintenance technology are also issues of concern. The lack of standardization of material forms and high fidelity, hierarchical design methodologies can result in overly conservative designs that, while providing performance gains and ensuring safety and durability, too often suffer in economy compared to conventional metals technology. Validated progressive failure analyses are also required to predict, without tests, the lifetime performance of composite structures.

Finally, the limited human resources with composites training and experience constrain broader applications [1].

It is also important to point out recent advances that are paving the way to meeting the challenges articulated above. NASA Langley recently successfully tested a full-scale composite wing structure (see Fig. 1) designed to meet the requirements of a 220-passenger commercial transport aircraft [2]. The wing box was 41 feet in length and incorporated advanced graphite fiber textile performs and Kevlar stitching for stringer-skin connections with resin-film-infusion to achieve resin impregnation. These manufacturing innovations by the Boeing Company were focused upon significant manufacturing cost reductions while meeting performance goals. The wing structure sustained 97% of design ultimate load prior to failure through a lower access opening and was, therefore, judged to have successfully met test requirements while providing further insight into refinements necessary for adoption of this new technology.

It should also be noted that the successful design and test of the NASA/Boeing wing structure required an extensive set of material, fabrication and sub-element tests to clarify manufacturability and the preliminary design. Thus, at the end of the 20th century composites technology is found to be largely based in empirical methods with the accompanying limits on economy (See Figure 2). These shortcomings in composites technology will only be overcome with the further developments in the areas described and through new emerging technologies.

Emerging Technologies

There are a number of emerging technologies that will expand the design space in the 21st century air vehicle and provide enhancements in performance, safety and economy. Smart materials and systems technology to control structural and aeroelastic response offer the opportunity to achieve structural and aeroelastic performance and efficiencies not possible with conventional materials and structures technology. Enhanced flutter, gust, buffet and maneuver load behavior can be achieved. Piezoelectric actuators have been successfully employed for active flutter suppression, active gust load alleviation and noise suppression [3]. Shape memory alloys have also been employed to address sonic fatigue and noise suppression issues. Smart structures have been developed to improve aerodynamic performance in such applications as the contoured, hingless flap and aileron with built-in shape memory alloy tendons. Efficiency gains of 8-12% have been achieved for lift, pitching and rolling moments over a broad range in wind tunnel tests [4]. The engine inlet has also been the subject of smart structures development in order to provide for its deformation to achieve optimum configurations for multiple flight conditions.

Synthetic jet actuators for control of flow separation have recently been employed to increase airfoil efficiency. The actuator has the capacity to provide both positive and negative pressure in the flow stream at a small diameter orifice and is thereby termed a “zero-mass flow” device [5]. Jets constructed of two piezoelectric/metal wafer laminates that are actuated by controlling sinusoidal frequency and phase to achieve the desired pressure characteristics. Jet velocities of 60-100 m/second have been achieved in the laboratory and active separation control at Reynold’s number up to 40X106 has been demonstrated to delay flow separation under flight conditions [6].

Multidisciplinary design optimization and flight control disciplines have been integrated to utilize localized flow control and distributed shape-change devices to achieve active flight control for tail-less aircraft. The integration of vehicle configuration, prediction of control moments with computational fluid dynamics, location of shape-change devices, and algorithm for optimum location of devices and simulation of the flight controls, was necessary. In addition, fluidic thrust vectoring, accomplished by deflection of the jet with a secondary air stream, has been examined for additional flight control [7].

Reliability-based design and certification require that new and robust methodologies be developed for high fidelity analysis of composite materials and structures [8]. This approach will replace the empirically based, factor-of-safety design with a design paradigm that features science-based methodology for critical design features. It relates weight, reliability and economics as multiple design merit functions. Process specific imperfections and defects and their impacts on response are considered directly. Progressive failure analyses are carried out with powerful design tools made possible by the integration of advanced modeling methods and scientific understanding. Finally, tailored composite applications based upon biologically inspired concepts to achieve optimum performance are being pursued.

Robust manufacturing technology to insure high performance aerostructures with increased cost-effectiveness has focused on the development of non-prepreg/autoclave systems. The integration of engineered textile preforms, stitching and vacuum-assisted resin transfer molding technology has been shown to provide significant advantages for future aircraft programs. Methods for prediction of manufactured quality, reproducibility and imperfections will be essential.

The field of biological sciences continues to provide new insights into the ways organisms have successfully adapted to their environment over millennia. The integration of materials, structures and aerodynamics simulations with the field of biomimetics provides the framework to develop a link between what nature has learned over time and the need for current aerospace solutions. These efforts require the development of design teams who have representation from the disciplines of biomimetics, materials science, aerostructures, computational fluid dynamics and computer science.

Nanotechnology can also be expected to provide the next generation of revolutionary materials technology for future aero vehicles. Discovered by Iijima [9] the single-walled carbon nanotube possesses extraordinary mechanical, electrical and thermal properties. Early evidence suggests that carbon nanotube/polymer composites will play a significant role in the future aero vehicle systems.

Technology Integration Benefits

The future of aeronautics will significantly benefit from the integration of the numerous advances discussed above and their exploitation will be based in advanced composites as the enabling technology [10]. For military aircraft, smart, flexible structures, synthetic jets, forebody vortex control, advanced control laws, passive porosity, continuous moldline technology and fluidic thrust vectoring will provide for increases in range, improvements in agility and survivability. For commercial transport vehicles, these technologies will provide active shape control, health monitoring, buffet load alleviation, active transition control, thrust vectoring, inlet and nozzle shaping, exterior noise suppression, vibration suppression, active separation control, gust load alleviation and flutter suppression.

Consider the contributions of these technologies for a conventional long haul/high capacity conventional subsonic transport aircraft. Laminar flow control, design optimization and excrescence drag reduction will yield a reduction of 4.6% in the take off gross weight (TOGW) of the vehicle [11]. Composite wing and tails, composite fuselage, light weight landing gear, advanced metals and aeroelastic tailoring will reduce TOGW by 24.3%. Advances in aero-mechanical propulsion design, hot section, materials and secondary systems can achieve a savings of 13.1%. Finally, in the systems area, relaxed static stability, fly-by-light/power-by-wire, high performance navigation and intelligent flight systems will yield a 9% savings in TOGW. Taken together these advances would yield an aircraft with an overall weight reduction of 51%. Of the total weight reduction, structures technology and composites would account for 48% of the total.

The blended wing body concept to produce a long haul/high capacity subsonic transport aircraft with a capacity of 800 passengers, a range of 8500 nautical miles and a landing requirement of 10,000 feet could achieve a 45.7% weight savings (TOGW) through the incorporation of advanced technology. Laminar flow control, design optimization, and excrescence drag reduction would yield 11.8% savings. Composite wing and fuselage, light weight landing gear and aeroelastic tailoring would reduce weight by 19.1%. In the propulsion arena advances in aero-mechanical design, hot section, materials, secondary systems, boundary layer ingestion would yield 12.2% and in the systems area, fly-by-light/power-by-wire, high performance navigation and intelligent flight systems would reduce weight by 2.6%. Clearly, the technology with the greatest impact on weight remains structures technology and composites for the blended wing body concept vehicle as well as the conventional concept discussed above.

21st Century Vision for Aeronautics Technology

Technology in the Digital Age will revolutionize high-speed mobility of humankind in a manner that will produce a sea change in human prosperity. This change will be not unlike the completion of the intercontinental railroad in the late 1800's or the introduction of the interstate highway system in the in the 1950's in the United States. Today's air mobility of citizens is limited by analog air traffic control systems, the number of trained pilots, the number of full-scale airports and the number and character of aircraft. Future Digital Airspace technology will provide the vehicle with "perfect knowledge" of terrain, geography, weather, vehicle condition, control and navigation through the central digital brain with extraordinary computational power. Embedded sensors and devices will yield smart materials and structures sufficient to achieve performance that allows vehicles to significantly increase performance and land safely on airfields that are insufficient in length for conventional aircraft. This revolution in technology will increase human mobility by an order of magnitude (See Figure 3. However, it is clear that the integration of the necessary technologies will lead to increased complexity of the air transportation system as well as air vehicles. Indeed, as the enhanced capability of the "digital machine" is increased, there will be a significant increase in system complexity such that the technology insertion will appear disruptive. During the next phase, however, increases in capability will result in only a corresponding linear increase in system complexity. It is during this period of technology innovation that the primary benefits described above will be realized.

The primary question to be answered is, "will the benefits in mobility, performance, safety, noise reduction, fuel economy be worth the price required to master complexity of the multifunctional vehicle and the "open space" air traffic control systems?" One need only examine the benefits of the digital processor in today's society, as described in Moore's Law to answer, yes! Computational power has doubled every eighteen months during the last several decades and it was the mastery of the complexity of modern microelectronics that is responsible for the extraordinary economic growth in much of the world today. Enhanced high-speed air mobility can be expected to produce no less result.

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Figures

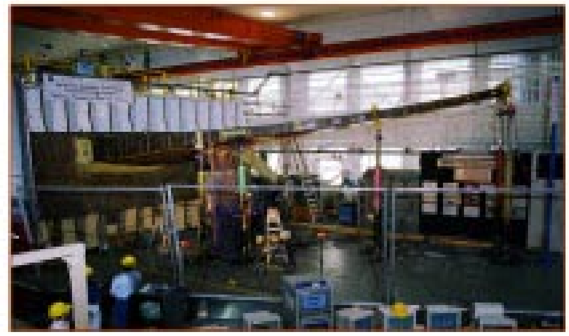

Fig. 1 Boeing – Langley composite wing test

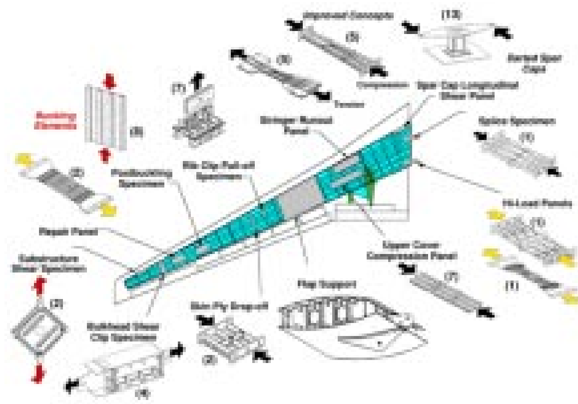

Fig. 2 Building block approach

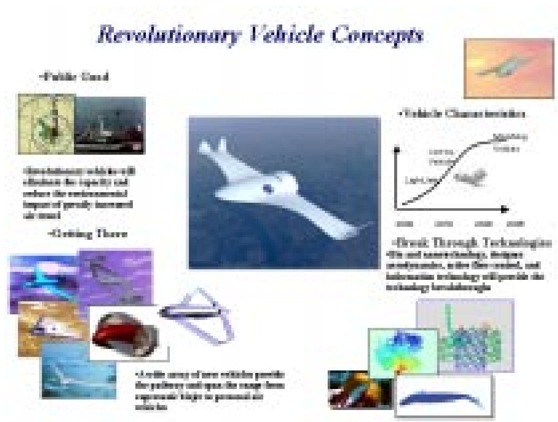

Fig. 3 Revolutionary vehicle concepts.